Magnetized Optics of the Fermilab Electron Cooler

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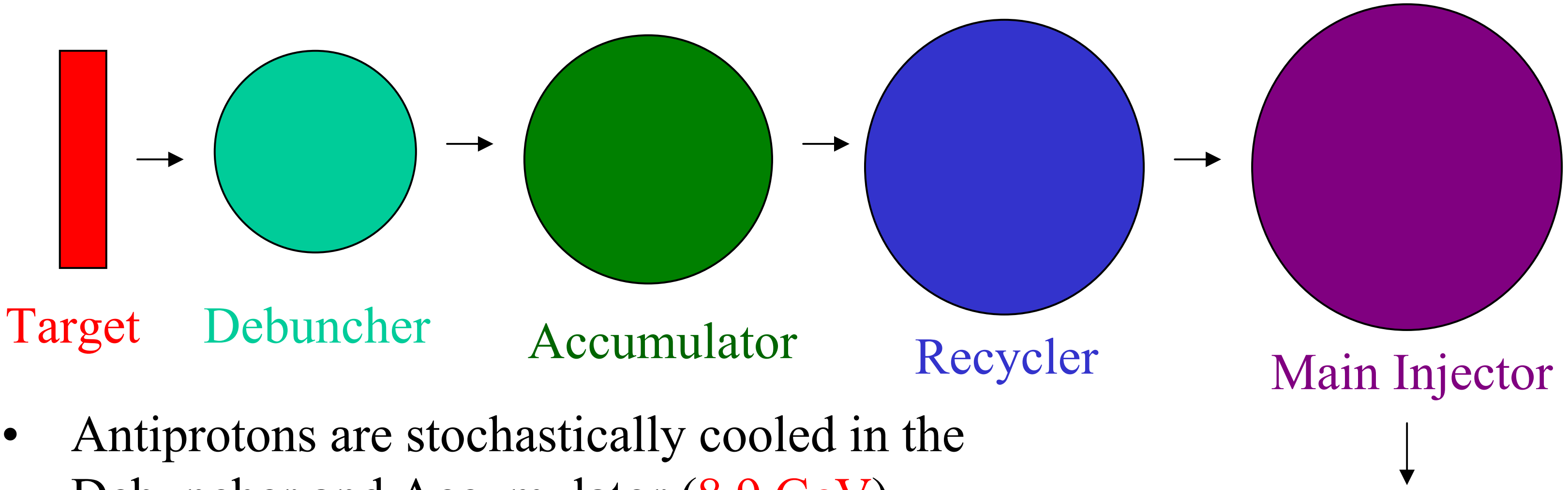
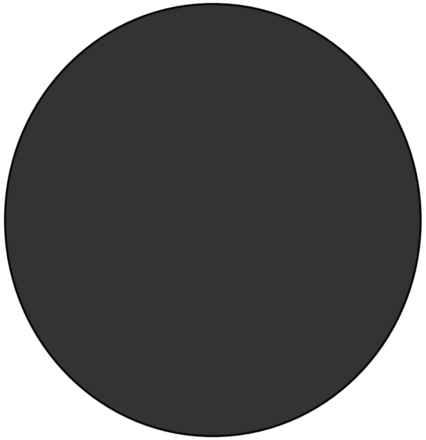
Antiproton Cooling at FNAL



Target Debuncher Accumulator Recycler Main Injector

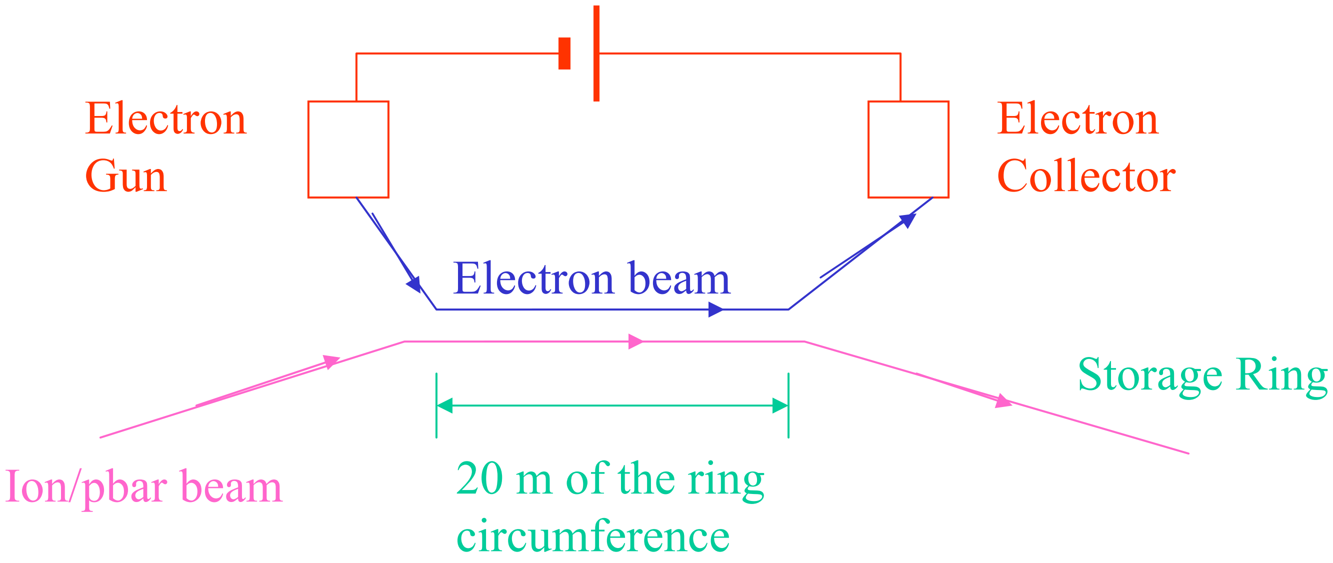


Tevatron

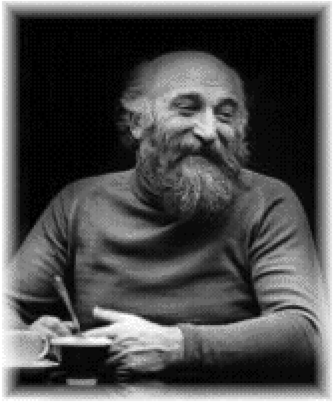
- Antiprotons are stochastically cooled in the Debuncher and Accumulator (8.9 GeV).
- Pbars are then injected in the Recycler, 20E10 within 10-15 eVs per every 30 min, and be stacked there up to 6E12 pbars within 30-50 eVs and 7-10 mm mrad of norm. 95% emittances.
- After that, they are transferred to the Main Injector, accelerated to 150 GeV, injected in the Tevatron, and used in p-pbar collisions at full energy 1 TeV.
- See more details in Ref. [1].

Principles of Electron Cooling

- A stored pbar beam is overlapped with a nearly monochromatic and parallel electron beam in a straight section of the storage ring
- The velocity of the electrons is made equal to the average velocity of the ions.

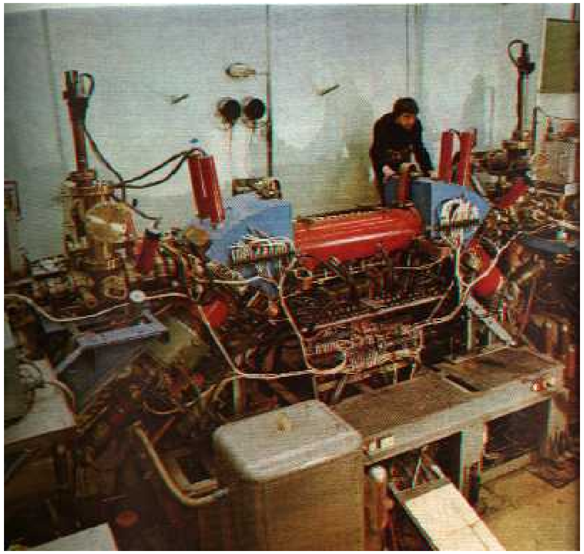


Electron cooling – the origin and the implementation



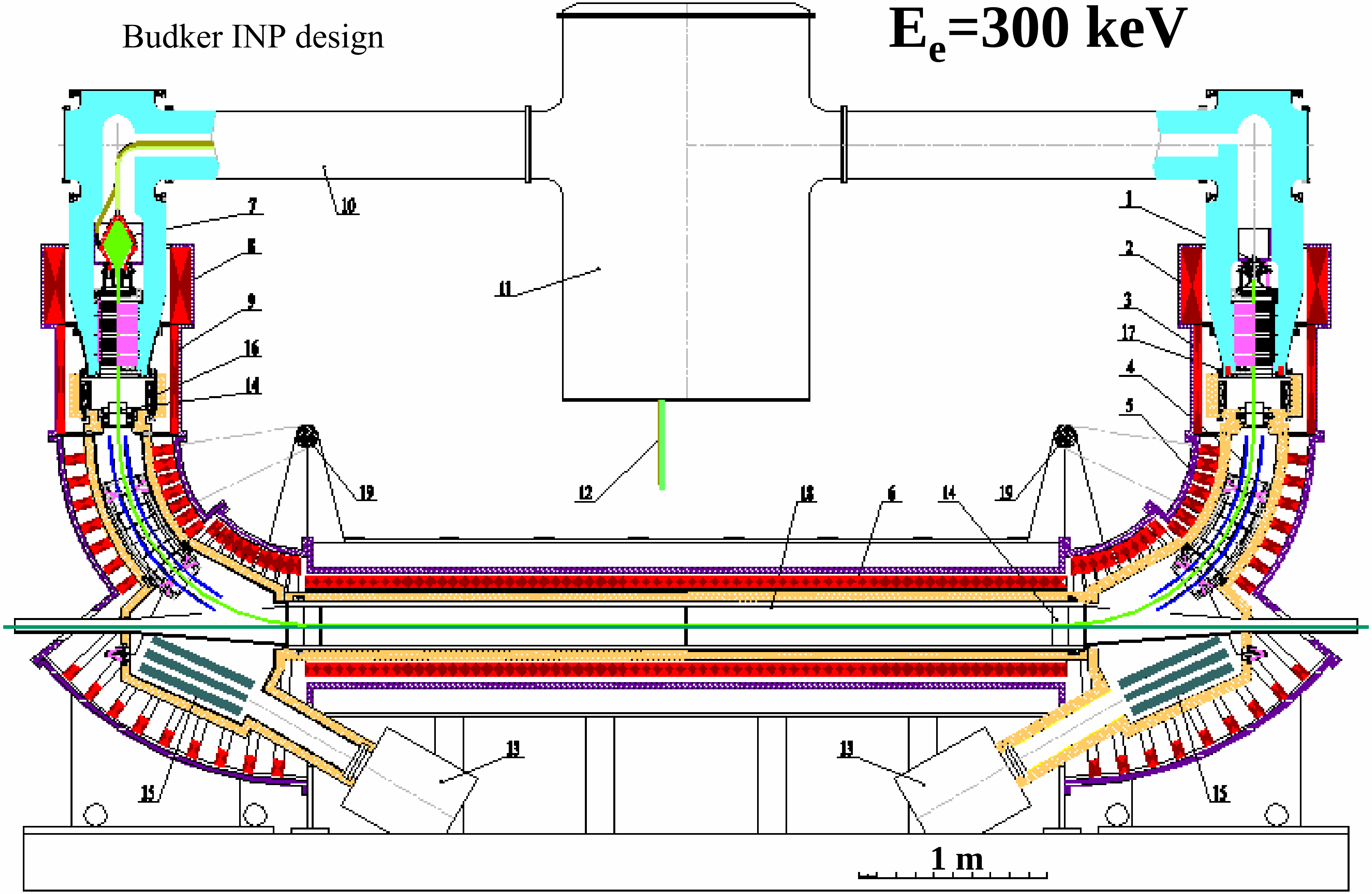
- Was invented by G.I. Budker (INP, Novosibirsk) as a way to increase luminosity of p-p and p-pbar colliders.

- First publication at Symp. Intern. sur les anneaux de collisions á electrons et positrons, Saclay, 1966: "Status report of works on storage rings at Novosibirsk"
- Electron cooling was first tested in 1974 with 68 MeV protons at NAP-M storage ring at INP. →
- CERN: ICE ring - 1979-80
- FNAL - 1982



Budker INP design

E_e=300 keV



1 - electron gun; 2- main “gun solenoid”; 4 - electrostatic deflectors;

5 - toroidal solenoid; 6 - main solenoid; 7 - collector; 8 - collector solenoid; 11 - main HV rectifier; 12 - collector cooling system.

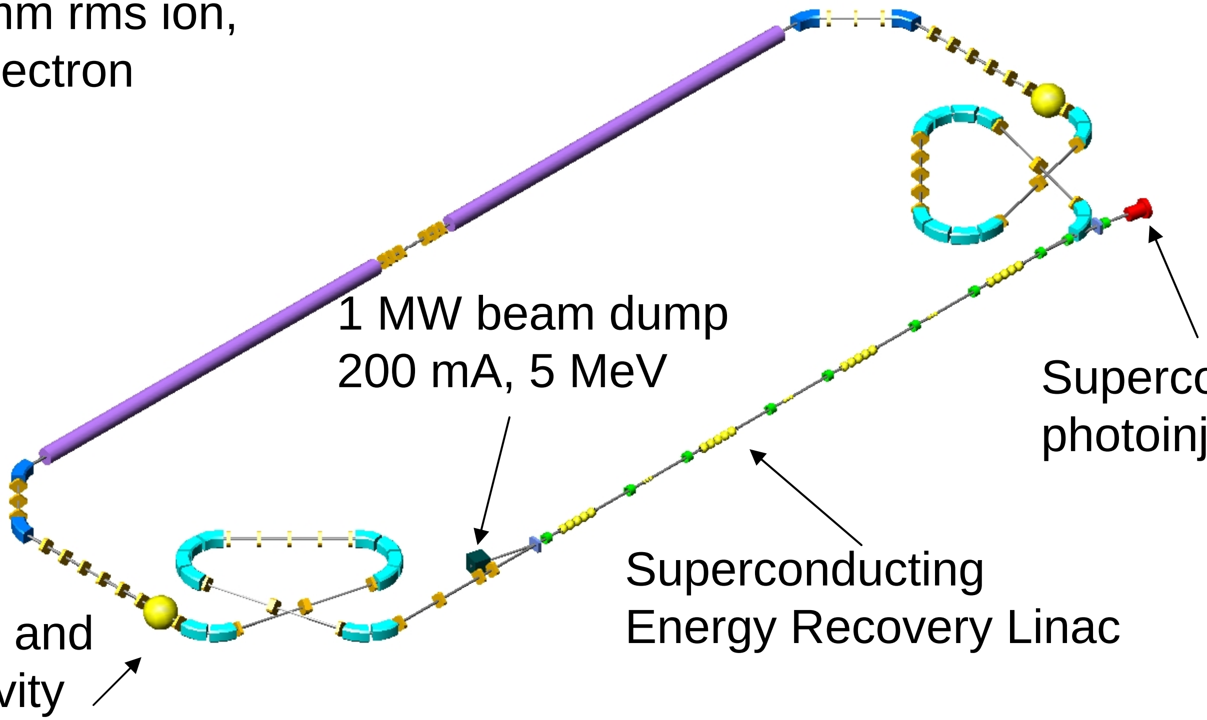
Magnetic field in the cooling section

- Low energies – kG-range field required for keeping the beam tightly focused against the space-charge forces.
- High energies – even though the SC forces are reduced, the magnetic field is still needed for focusing and/or to give the highest possible cooling rates.
- In principle, a continuous solenoid along the whole electron beam line would be a good focusing option at any energy. This is hardly possible at energies of $\gamma > 1.5$. Lumped focusing can be used for the beam transport line with the design goal of avoiding any coherent motion of the beam inside the cooling solenoid.

The RHIC Electron Cooler

Two solenoids: 13-m, 50-kG ea.

Beam size: 1mm rms ion,
0.7 mm rms electron



1 MW beam dump
200 mA, 5 MeV

Superconducting
photoinjector

Superconducting
Energy Recovery Linac

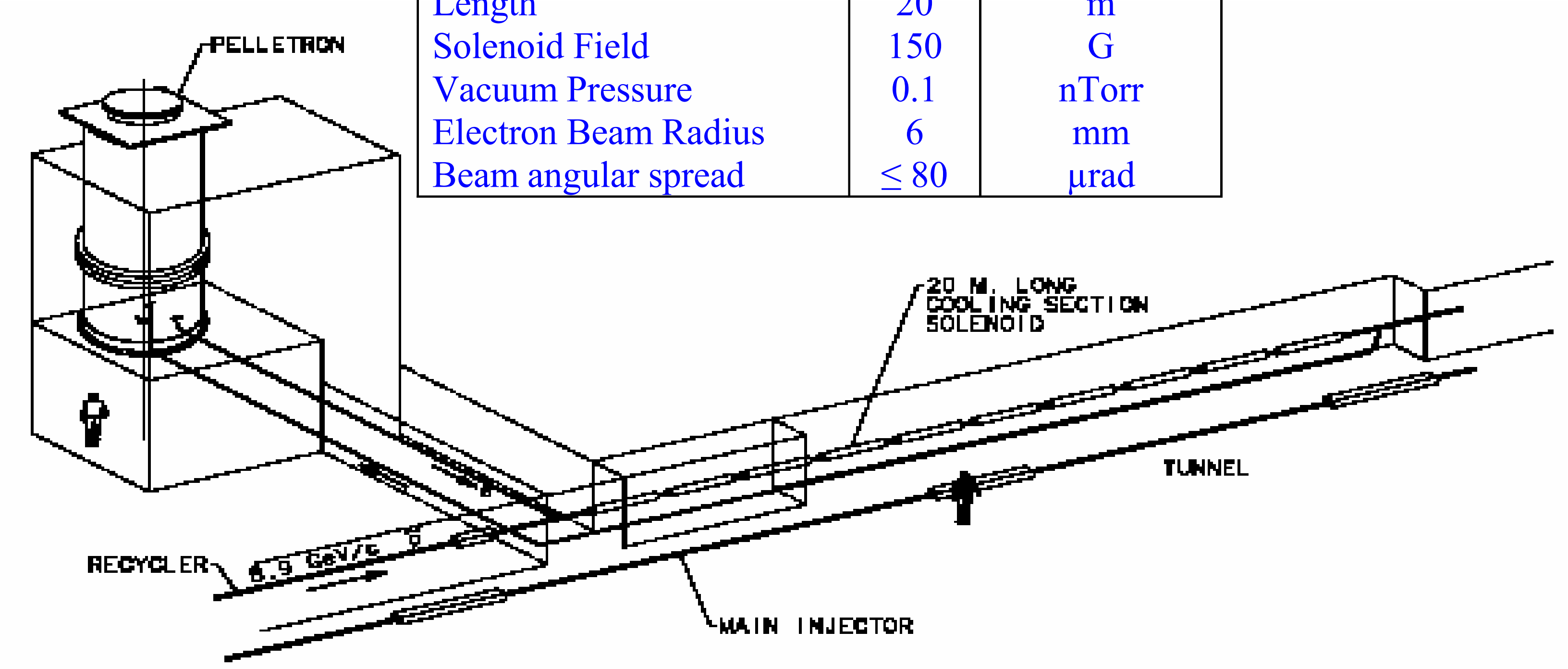
Stretching loop and
debunching cavity

54 MeV electron beam for cooling 100 GeV/A (gold ions and protons.
Must use superconducting Energy Recovery Linac.
Need 20 nC electron bunches at 9.4 MHz.
The emittance is challenging.

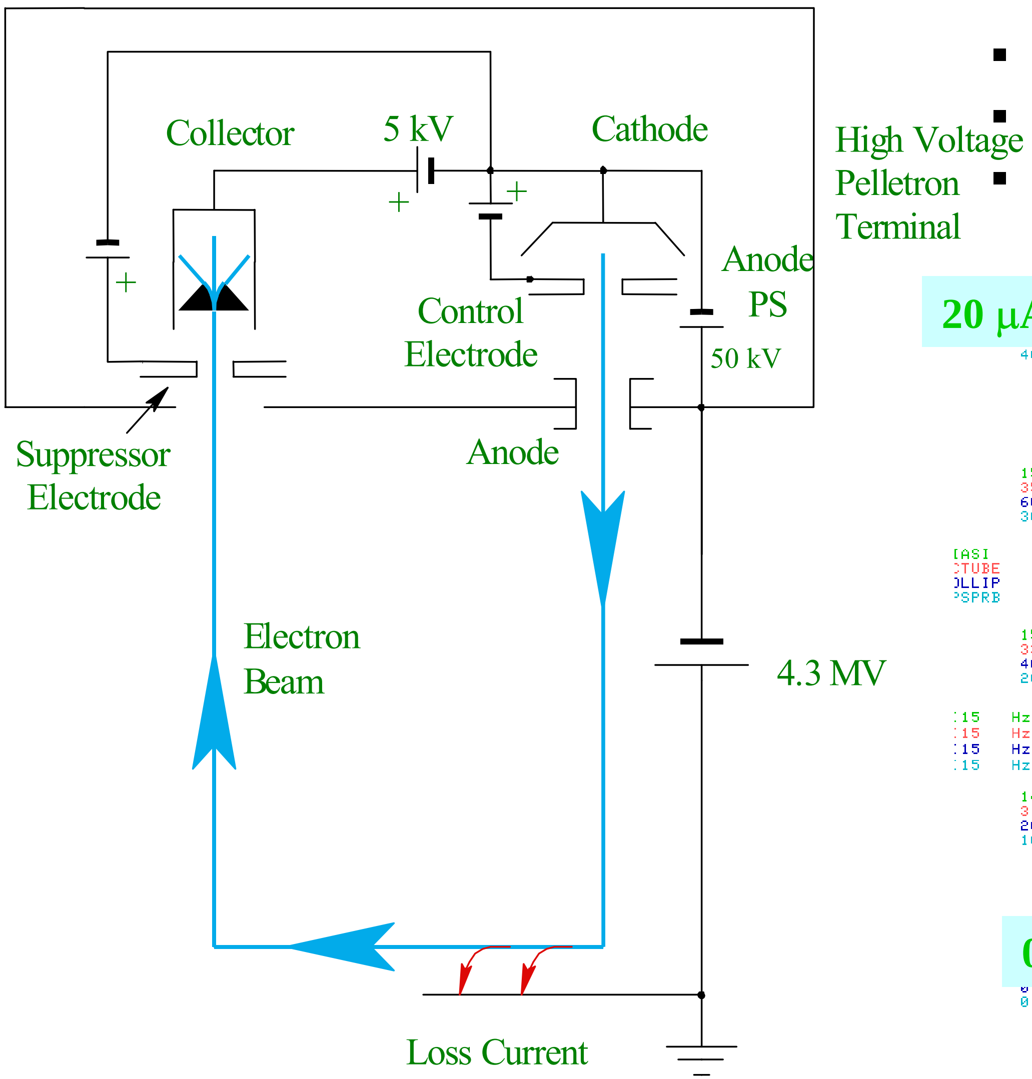
Schematic Layout of the Fermilab Electron Cooling

Electron Cooling System Parameters

Parameter	Value	Units
Electrostatic Accelerator		
Terminal Voltage	4.3	MV
Electron Beam Current	0.5	A
Terminal Voltage Ripple	500	V (FWHM)
Cathode Radius	2.5	mm
Gun Solenoid Field	600	G
Cooling Section		
Length	20	m
Solenoid Field	150	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Beam angular spread	≤ 80	µrad

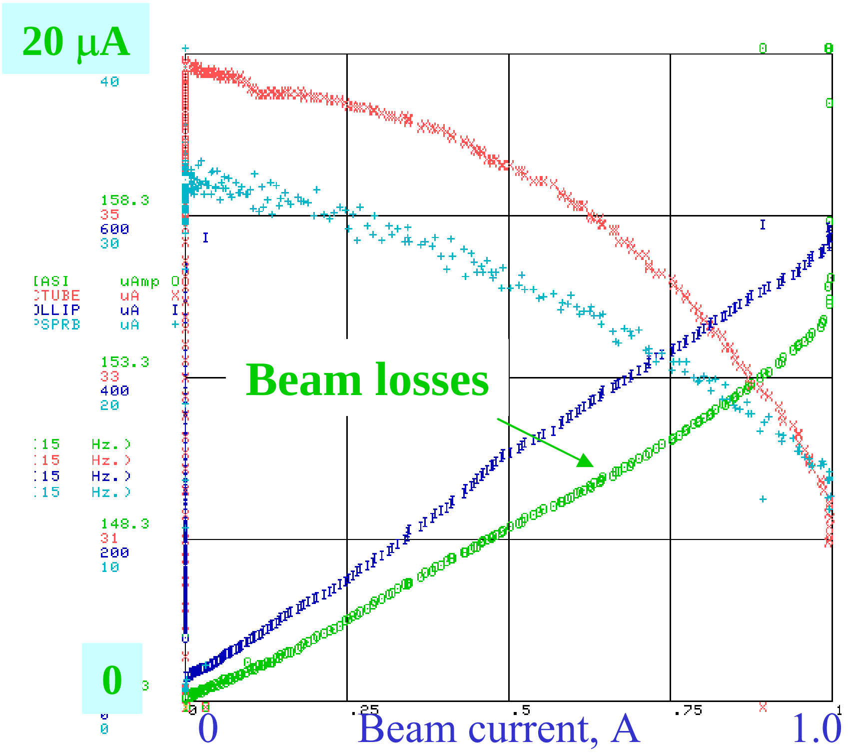


Simplified electrical schematic of the electron beam recirculation system.

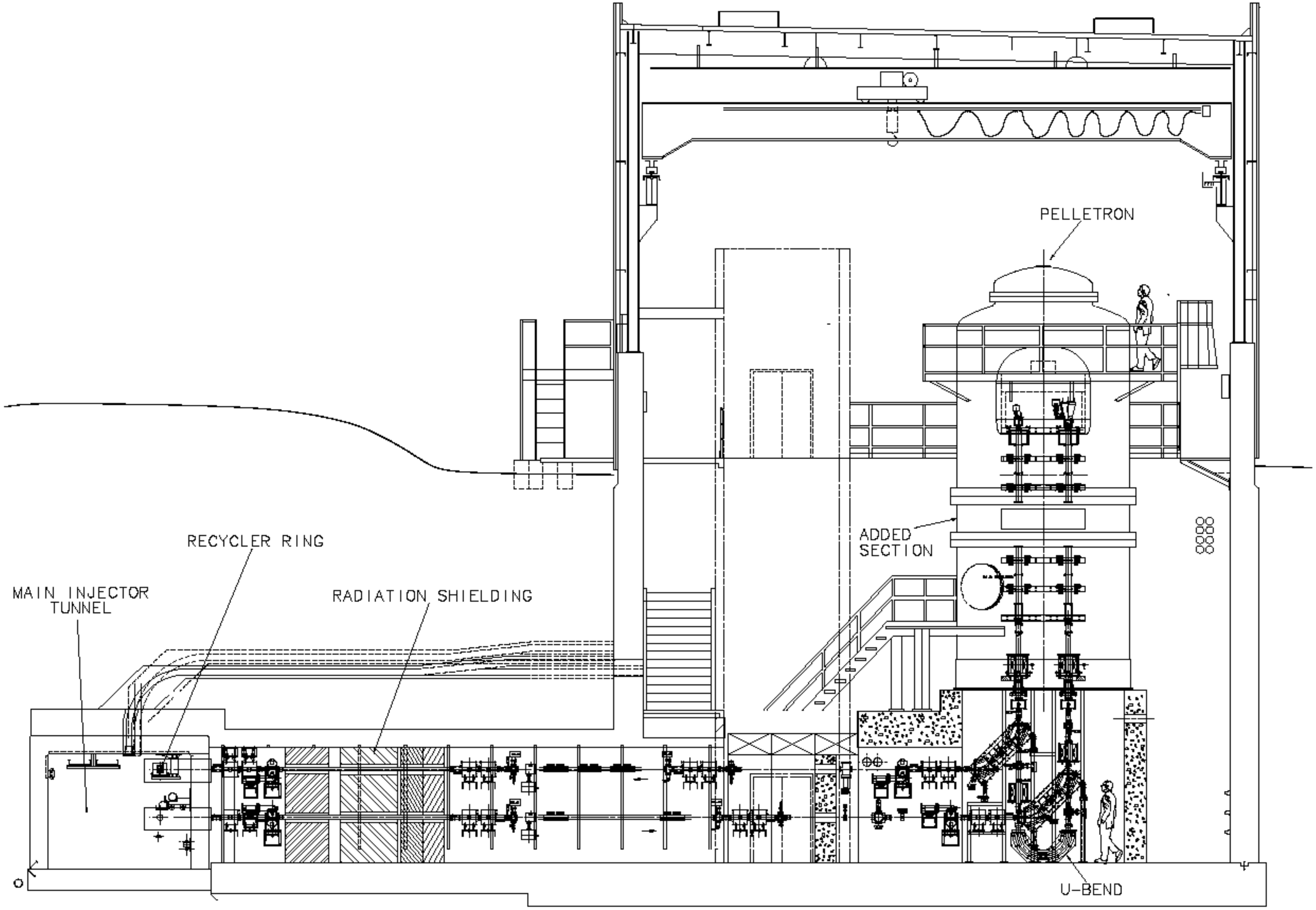


For I= 0.5 A, ΔI_{loss}= 5 μA:

- Beam power 2.15 MW
- Current loss power 21.5 W
- Power dissipated in collector 2.5 kW



Fermilab electron cooling system layout



Cooling section solenoid

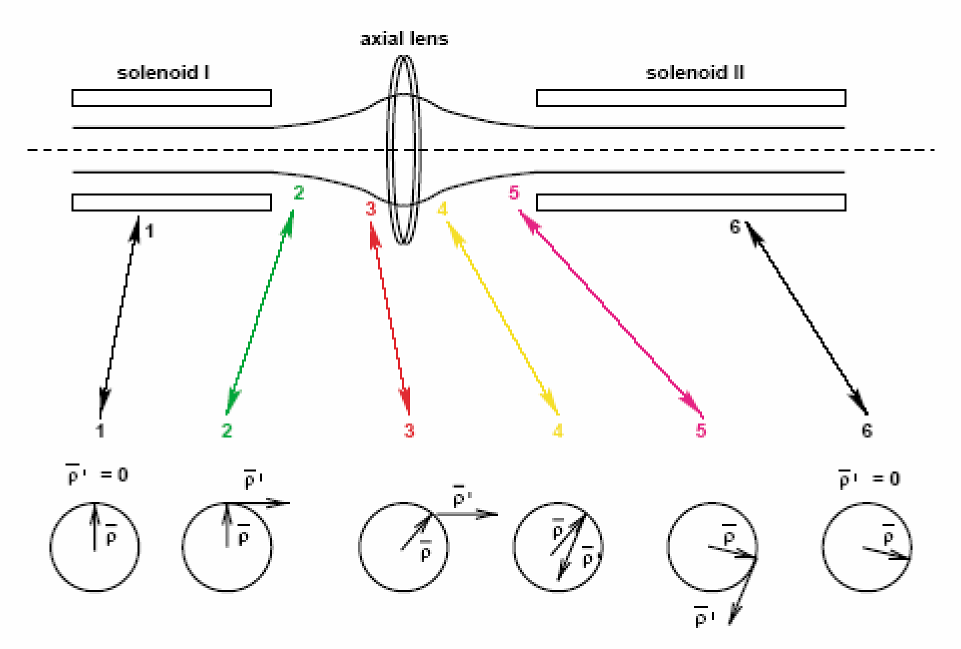
Optics requirements

- A beam state required by electron cooling is characterized by a high ratio between the beam size and the Larmor radius; this state is referred to as calm or magnetized.
- On entering or exiting the solenoid, the beam acquires a kick that changes its rotational state. Inside the cooling solenoid, the beam is required to be calm, i.e., not to have any angles in excess of the thermal ones.
- If *a* is the required beam radius in the cooling solenoid, the following condition needs to be met:

$$a' = 0,\ aB^2 = \pm a_0 B_0{}^2$$

Matching between solenoids

An example of a simplest axially symmetric beam matching between two solenoids.



When can solenoids be interrupted?

- Single particle paraxial-ray equation:

$$r'' + \frac{\gamma' r'}{\beta^2\gamma} + \left(\frac{eB}{2pc}\right)^2 r - \left(\frac{eB_0}{2pc}\right)^2 \frac{r_0^4}{r^3} = K\frac{r}{a^2} - \frac{\gamma'' r}{2\beta^2\gamma}$$

- Contains a term, which looks like an effective emittance:

$$\varepsilon_{eff} = \frac{eB_0 r_0^{\,2}}{2pc} = \frac{e\Phi}{2\pi pc}$$

- This analogy leads to a concept of an effective β-function

$$\beta_{\mathrm{eff}} = a^2/\varepsilon_{\mathrm{eff}} = \frac{2\pi\gamma\beta e a^2}{r_e\Phi}$$

When can solenoids be interrupted? (cont'd)

- For a 25-kV electron cooler, 1-kG field and a 1-cm radius beam one has $\beta_{eff} = 1$ cm – it means the accompanying magnetic field can not be actually interrupted.
- This situation changes for relativistic coolers. At Fermilab for a 4.3-MeV (KE) beam, 100-G solenoid field and a 0.6-cm beam radius in the cooling section, we can interrupt the solenoid field quite early in the acceleration process ($\beta\gamma = 2$) where $\beta_{eff} > 20$ cm.

Beam transport line

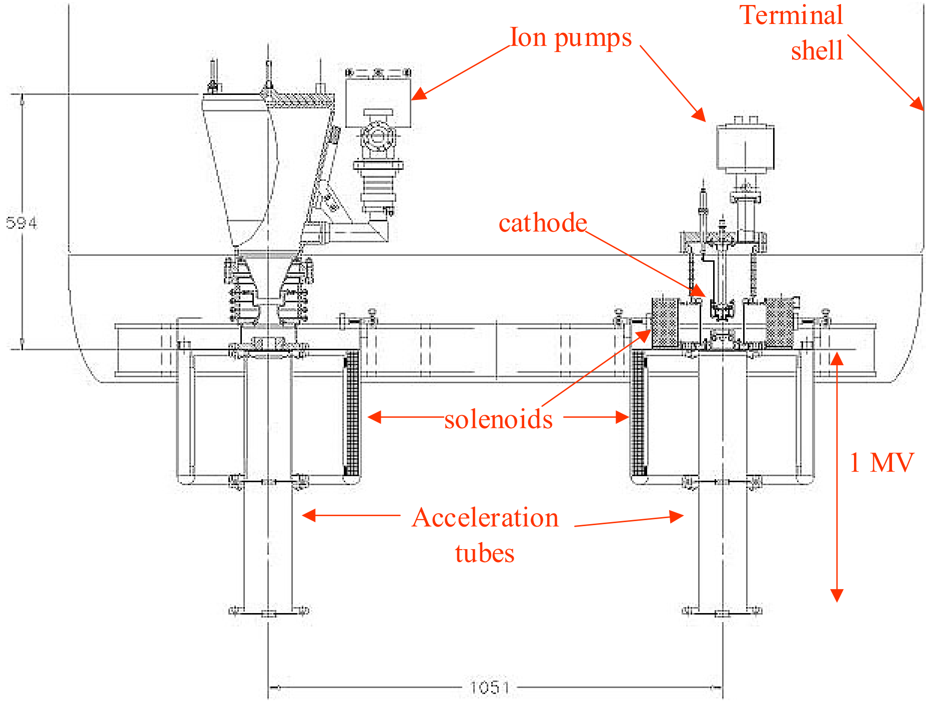
- Angular momentum dominated beam transport
  - Beam transport optics from the exit of the gun solenoid to the entrance of the cooling section is dictated by three beam properties:

    (1) A large emittance-like contribution from the angular momentum

    $\varepsilon_{N,eff} = eBr_c^2 /(2mc^2)$. For B = 600 G, r_c = 0.25 cm, $\varepsilon_{N,eff} \approx$ 100 mm-mrad

    (2) Low beam aberrations

    (3) High optics stability and reproducibility



Optical Requirements

- Pbar optics is fully described by the requirement to have cooler's beta-function as small as possible, i. e. of 20-30 m (about the cooler length). While the cooling rates are rather weakly sensitive to the beta-function ($\propto \sqrt{\beta}$), the electron angle requirements are a tough issue: $\theta_e \cong \sqrt{\varepsilon_p / \beta}$.
- Electron beam is angular momentum dominated [3]. This means that its effective emittance is determined by the magnetic field at the cathode, while the temperature is irrelevant. Such beams have a sharp transverse boundary.
- Electron optics has to satisfy the following requirements:
  - Parallel and round e-beam of radius 4-6 mm in the cooler;
  - No dispersion in the cooler, small or zero dispersion in the accelerator;
  - Envelope maximums are limited to avoid nonlinear aberrations - half-axes ~ 1 cm upstream of the cooler;
  - Preferably no flips of the angular momentum - to reduce the Touschek effect;
  - Round and well-focused beam in the deceleration section.

Electron Beam in the Cooler

- Properties of the e-beam in the cooler follows from a requirement to optimize the cooling process.
  - Electron angles have to be smaller than angles of "tail" antiprotons. This sets a limit on the r. m. s. electron angles in the cooler $\theta_e \le (2-3)\sqrt{\varepsilon_p / \beta}$. If this condition is not satisfied, the cooling rates are reduced as $1/\theta_e^3$.
  - Electron beam has to cover "tail" antiprotons. This means that it has to be round with the radius $a_e \cong (2-3)\sqrt{\varepsilon_p \beta}$.
  - The beam have to be focused to suppress space charge, ions and image charge perturbations.
- All this requires magnetic field in the cooler $B_{cooler} \cong 50-100\ \mathrm{G}$.
- The generalized Busch's theorem [3] leads to a requirement of the magnetic field at the cathode, matched with the field at the cooler by the flux preservation:

$$Ba_e^2\Big|_{cooler} = Ba_e^2\Big|_{cathode}$$

Beam Rounding: General

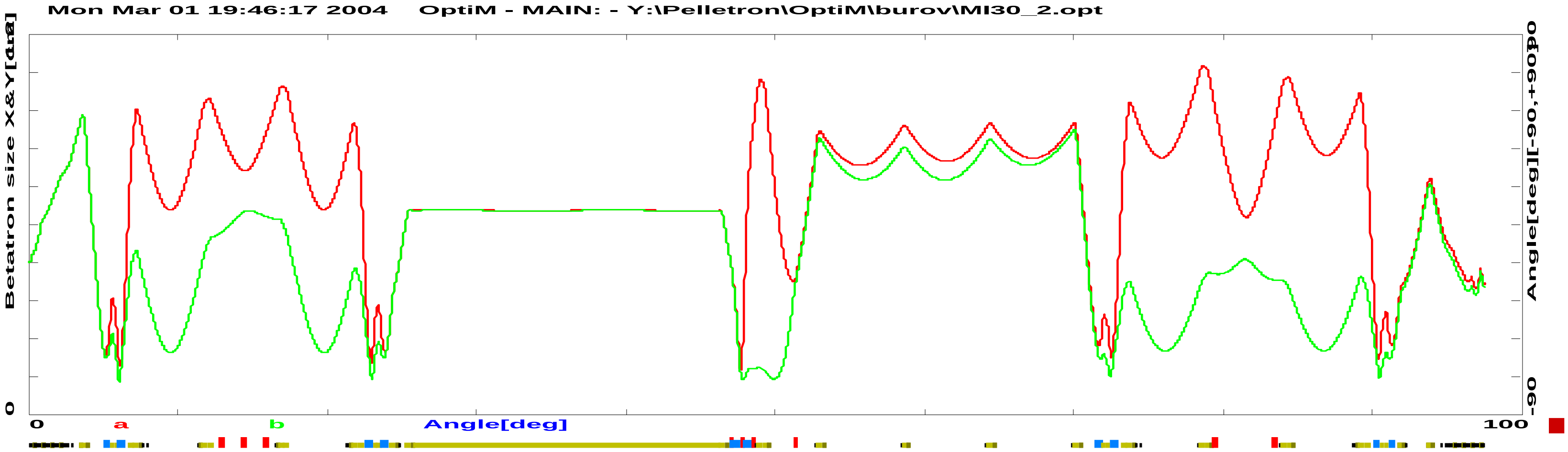
- The beam is round (axially symmetric) at the round cathode.
- The beam is round during acceleration due to the fields symmetry.
- The beam axial symmetry is broken by the 45° dipoles (index=0 and the fringe focusing asymmetry).
- To preserve beam symmetry for any initial conditions, the 4D transfer matrix has to be a product of a block-identity and rotation [4]:

$$M_{4\otimes 4} = R(\theta)\begin{pmatrix} M_{2\otimes 2} & 0_{2\otimes 2} \\ 0_{2\otimes 2} & \pm M_{2\otimes 2} \end{pmatrix}$$

- Thus,
  - To complete any uncoupled matrix to invariant, 3 quads are sufficient.
  - To complete a general 4x4 matrix to invariant, 6 quads are sufficient.
- In special cases, more elegant solutions for the rotational invariance are available.

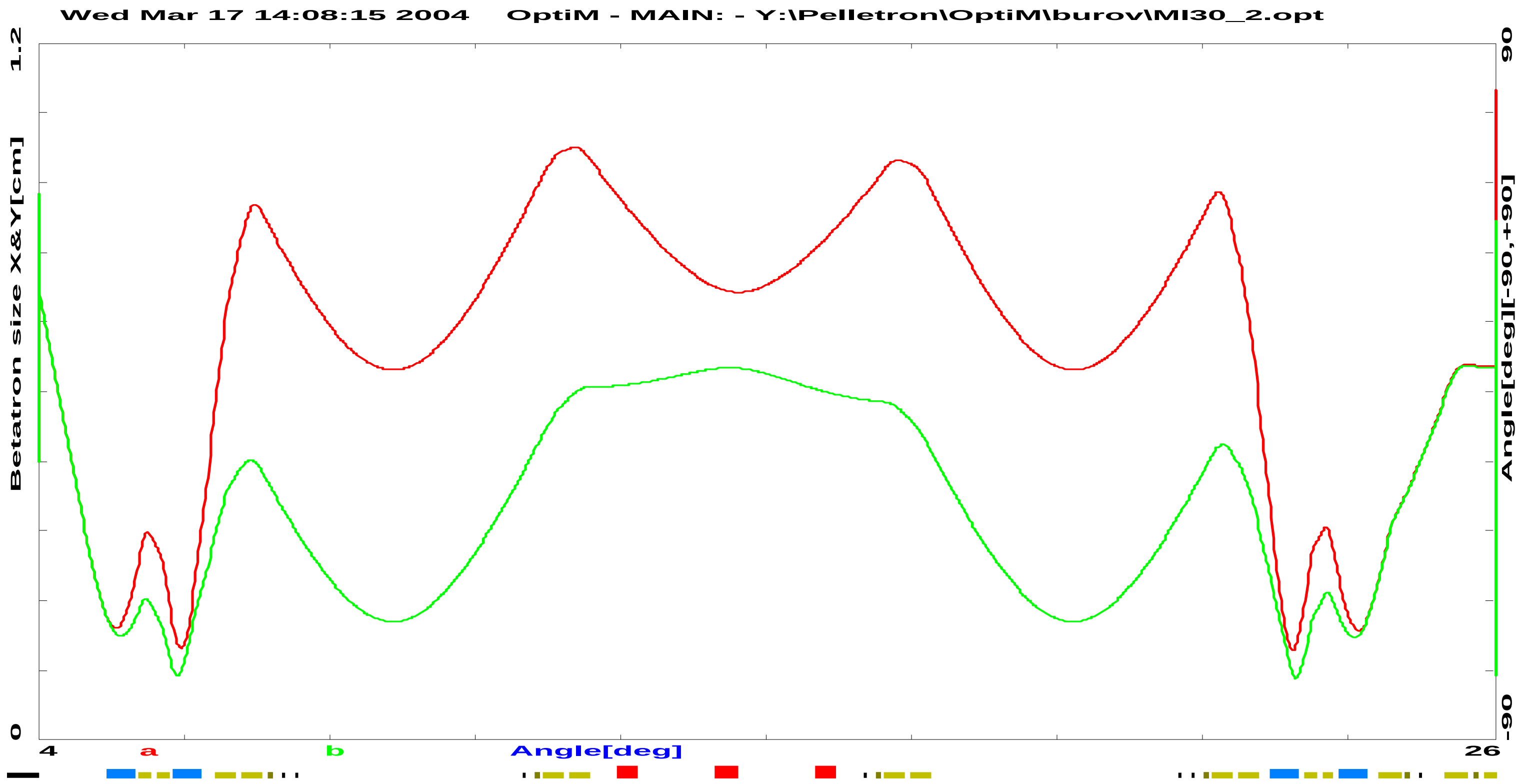
Beam Envelope

- Figure shows design envelope of the cooler made with the OptiM code [5]. Due to the angular momentum domination, the beam boundary is well-defined.
  - The beam is round in the accelerating tube.
  - The invariance is broken at the first 90° bend.
  - The invariance is restored after the second 90° bend, and the beam is round again in the cooling section. It is also parallel here.
  - The invariance is broken by the dispersion-suppressing quad inside the U-bend and almost restored by a solenoidal dublet and a quad
  - The mirror symmetry of the transfer line restores the invariance
  - The beam is round in the deceleration section.
- Outside of the bends, dispersion is zeroed.



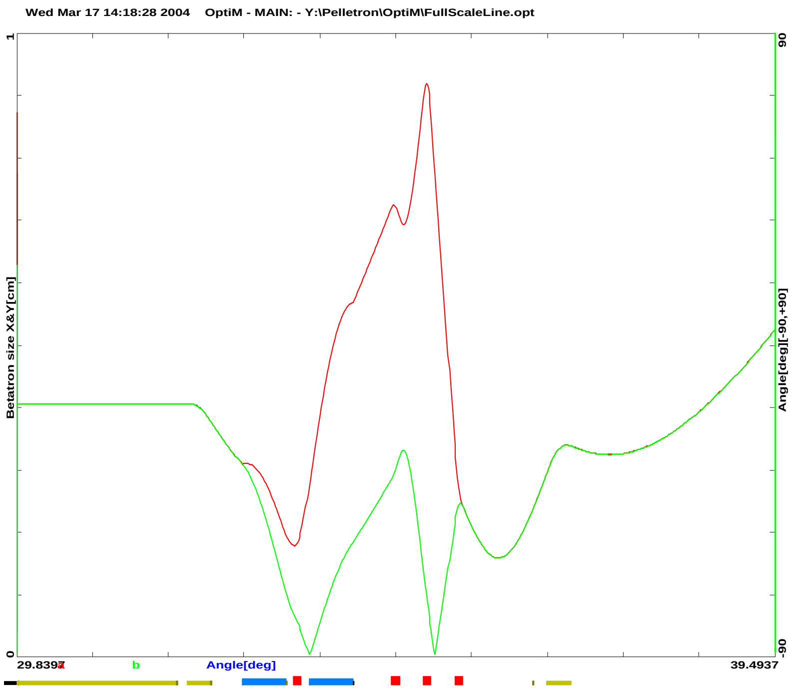
Rounding by lattice symmetry

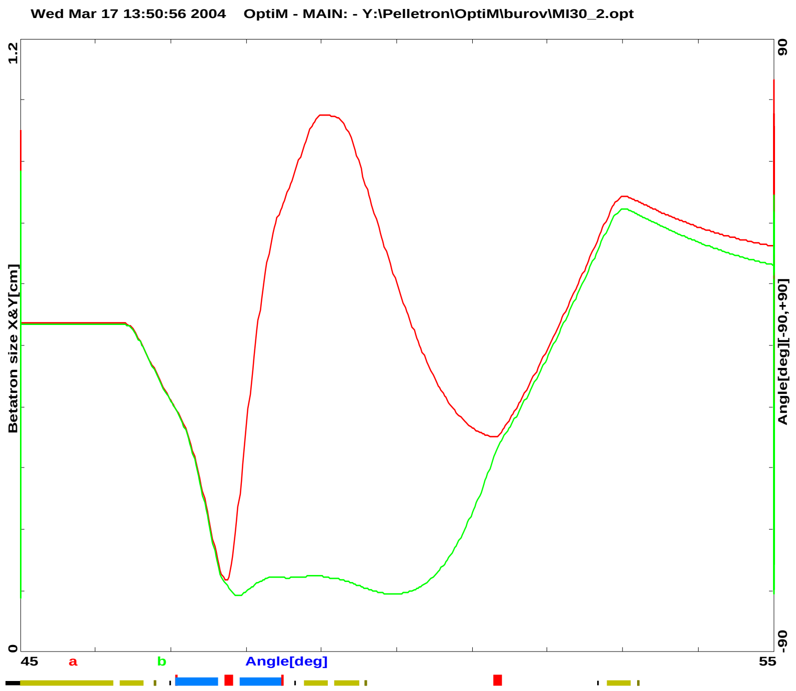
- The beam is rounded in the cooler with all the upstream quads zeroed. This is possible due to the mirror symmetry of the supply lattice.



Rounding at U-bend

- After the cooler, the symmetry is broken by the dispersion-killing quad inside the U-bend.
  - For the prototype line, the invariance is restored by means of the 3 quads (fig. left)
  - For the cooler’s design, the symmetry is restored with a ± solenoid dublet and a single quad. This solution requires the dipoles to be totally invariant (fig.right).





Ion clearing

- Ions affect electron beam optics even when ion density is very low ($\sim\gamma^{-2}$)
- Ion clearing is accomplished by using ALL bpms as clearing electrodes. Without clearing, problems with optics and stability begin at electron beam currents above ~10 mA.
- Bunched beams might not necessarily make the ions unstable.
  - Example: 80pC, 4ps, 80MHz rep. rate, I_{ave}~7 mA
  - Common ions (H_2, CO) are stable in cw regime.

Summary of electron angles in the cooling section

Component	Upper limit, µrad	Prototype result, µrad	Measured by	Required resolution of diagnostics
Temperature	90	No meas.	Pepper pot image at OTR monitor	50 µm in the OTR image
Aberration	90	~ 40	Pepper pot image at OTR monitor; BPMs	150 µm in OTR image; 50 µm in BPMs
Envelope scalloping	100	100	Movable orifices	500 µm in beam dimension measurements
Dipole motion caused by magnetic field imperfections	100	~ 200	BPMs	30 µm in "DC" BPM resolution; 50 µm in BPMs' offsets measured wrt pbar beam
Beam motion	50	30	BPMs	50 µm in BPM signal in 100 Hz bandwidth
Drift velocity	20	No meas.	Calculated	
Total	**200**	**~ 300**		

Final remarks

- Optics is adjusted such that the beam is round and matched to the cooling section solenoid to cancel the beam rotation.
- At low beam energies and high average beam currents (0.5 A), the dc magnetic field of beam itself might already affect dipole fields at 10^{-4} level.
- Angular momentum flips in the beam optics should be avoided.
- Ion clearing is essential.

References

1. A. Burov, "Antiproton stacking in the Recycler", FERMILAB-CONF-03-171 (2003).
2. A. Shemyakin et al., "Test of a full-scale prototype of the Fermilab electron cooler", APAC '04 (2004).
3. A. Burov, S. Nagaitsev, A. Shemyakin, Ya. Derbenev, "Optical principles of beam transport for relativistic electron cooling", Phys. Rev. ST-Accel. Beams **3**, 094002 (2000).
4. A. Burov, S. Nagaitsev, Ya. Derbenev, "Circular modes, beam adapters, and their applications in beam optics", Phys. Rev. E **66**, 016503 (2002).
5. V. Lebedev, A. Bogacz, "Betatron motion with coupling", JLAB-ACC-99-19 (1999).
6. A. Burov, S. Nagaitsev, A. Shemyakin, "Energy distribution in a relativistic DC electron beam", FERMILAB-TM-2133 (2000).